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HEMODYNAMIC RESPONSE TO MODULATED STRESS CONDITIONS VIA POSTURAL INSTABILITY IN VIRTUAL REALITY: FNIRS STUDY[a]

RESPUESTA HEMODINÁMICA A CONDICIONES DE ESTRÉS MODULADO A TRAVÉS DE INESTABILIDAD POSTURAL EN REALIDAD VIRTUAL: ESTUDIO FNIRS

RESPOSTA HEMODINÂMICA A CONDIÇÕES DE ESTRESSE MODULADAS POR MEIO DE INESTABILIDADE POSTURAL EM REALIDADE VIRTUAL: ESTUDO FNIRS

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Keywords: virtual reality, fNIRS, disruption of balance function, stabilometry, eye movements.

Palabras clave: realidad virtual, fNIRS, alteración de la función del equilibrio, estabilometría, movimientos oculares.

Palavras-chave: realidade virtual, fNIRS, alteração da função do equilíbrio, estabilometria, movimentos oculares.

ABSTRACT

Introduction: The study of brain mechanisms and their localization in the processes of perception of volumetric moving stimulation in virtual reality and its influence on the formation of the image of the body position in space is a significant direction in modern neuroscience. Objective: The aim of this study was to identify changes in brain activity and postural stability indicators during induced stress exposure by disrupting the balance function in virtual reality. Method: 26 women (average age 21 years) participated. The experiment consisted of a 2-series design with an optokinetic presentation in VR conditions. The speed (30 and 60 degrees per second) and the direction of rotation of the optokinetic drum (right and left) were changed. A 24-channel fNIRS Brite Artinis Medical Systems BV was used. ST-150 stabilometry complex. VR device HTC Vive Pro Eye. The task is to track oculomotor behavior and gaze fixation in the central area of VR and to respond by pressing a key on the computer keyboard when sensations of a change in body position occur. Results: Differences in the quality of the balance function were revealed depending on the conditions of influence of the "Speed" factor (f = 8.984b; df = 1; p = < 0.006). Differences in the right parietal region: in the Rx8-Tx10 channel by the factors "Rotation speed" (f = 5.433b; df = 1; p = < 0.028), "Gaze movement dynamics" (f = 5.433b; df = 1; p = < 0.025), "Rotation speed + Eye movement dynamics" (f = 6.115b; df = 1; p = < 0.021). Conclusion: The obtained data indicate the importance of gaze control parameters in maintaining the functional state during optokinetic exposure in virtual reality conditions.

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R E S U M E N

Introducción: El estudio de los mecanismos cerebrales y su localización en los procesos de percepción de la estimulación volumétrica en movimiento en la realidad virtual y su influencia en la formación de la imagen de la posición del cuerpo en el espacio es una dirección importante en la neurociencia moderna. **Objetivo:** El objetivo de este estudio fue identificar cambios en la actividad cerebral y los indicadores de estabilidad postural durante la exposición al estrés inducido al interrumpir la función de equilibrio en la realidad virtual. **Método:** Participaron 26 mujeres (edad media 21 años). El experimento consistió en un diseño de 2 series con una presentación optocinética en condiciones de VR. Se cambiaron la velocidad (30 y 60 grados por segundo) y la dirección de rotación del tambor optocinético (derecha e izquierda). Se utilizó un fNIRS de 24 canales Brite Artinis Medical Systems BV. Complejo de estabilometría ST-150. Dispositivo de VR HTC Vive Pro Eye. La tarea consiste en rastrear el comportamiento oculomotor y la fijación de la mirada en el área central de VR y responder presionando una tecla en el teclado de la computadora cuando se producen sensaciones de un cambio en la posición corporal. **Resultados:** Se revelaron diferencias en la calidad de la función de equilibrio en función de las condiciones de influencia del factor “Velocidad” (f = 8,984b; gl = 1; p = < 0,006). Diferencias en la región parietal derecha: en el canal Rx8-Tx10 por los factores “Velocidad de rotación” (f = 5,433b; gl = 1; p = < 0,028), “Dinámica del movimiento de la mirada” (f = 5,433b; gl = 1; p = < 0,025), “Velocidad de rotación + Dinámica del movimiento ocular” (f = 6,115b; gl = 1; p = < 0,021). **Conclusión:** Los datos obtenidos indican la importancia de los parámetros de control de la mirada en el mantenimiento del estado funcional durante la exposición optocinética en condiciones de realidad virtual.

R E S U M O

Introdução: O estudo dos mecanismos cerebrais e sua localização nos processos de percepção da estimulação volumétrica em movimento na realidade virtual e sua influência na formação da imagem da posição do corpo no espaço é uma direção significativa na neurociência moderna. **Objetivo:** O objetivo deste estudo foi identificar mudanças na atividade cerebral e nos indicadores de estabilidade postural durante a exposição ao estresse induzido pela interrupção da função de equilíbrio na realidade virtual. **Método:** Participaram 26 mulheres (idade média de 21 anos). O experimento consistiu em um desenho de 2 séries com uma apresentação optocinética em condições de VR. Foram alteradas a velocidade (30 e 60 graus por segundo) e a direção de rotação do tambor optocinético (direita e esquerda). Foi utilizado um fNIRS de 24 canais da Brite Artinis Medical Systems BV, complexo de estabilometria ST-150 e dispositivo de VR HTC Vive Pro Eye. A tarefa consistia em rastrear o comportamento oculomotor e a fixação do olhar na área central da VR e responder pressionando uma tecla no teclado do computador quando surgissem sensações de mudança na posição corporal. **Resultados:** Foram reveladas diferenças na qualidade da função de equilíbrio em função das condições de influência do fator “Velocidade” (f = 8,984; gl = 1; p = < 0,006). Diferenças na região parietal direita: no canal Rx8-Tx10 pelos fatores “Velocidade de rotação” (f = 5,433; gl = 1; p = < 0,028), “Dinâmica do movimento do olhar” (f = 5,433; gl = 1; p = < 0,025), “Velocidade de rotação + Dinâmica do movimento ocular” (f = 6,115; gl = 1; p = < 0,021). **Conclusão:** Os dados obtidos indicam a importância dos parâmetros de controle do olhar na manutenção do estado funcional durante a exposição optocinética em condições de realidade virtual.

Integration of incoming visual, vestibular and proprioceptive information provides perception of the position and orientation of the human body in space, detection of the presence or absence of its movement [4]. The specific characteristics of the surrounding world are transfered through initially independent systems, thus, the perception quality is impacted by the terms of reception of separate sensory information. This leads to the formation of a complex coordinated representation of the spatial position of the body [1].

On the one hand, in addition to processing information about the shape and color of objects, the visual system also detects the movement of objects around the person, as well as the movement of the observer themselves. At the same time, information about the movement of a person's own body comes from the proprioceptive and vestibular systems and participates in providing different functions. For example, the information coming from proprioceptive system allows to control posture and balance of a body. At the same time, visual-vestibular interaction is the basis for maintaining a person's postural stability. These systems usually work in coordination in quotidian life, but an issue arises when the incoming

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information from the visual and vestibular systems does not coincide, which is reflected in what is known as sensory conflict [25], a mismatch between the incoming signals from the vestibular, proprioceptive, and visual sensory systems that are involved in determining a person's posture and orientation in space. On a subjective level, this mismatch can produce the illusion of body movement, as well as a number of associated discomfort symptoms such as dizziness and nausea [10]. The theory of sensory conflict provides an explanation of the interaction between the visual and vestibular systems in case of a discrepancy of information. Taking into account all sensory and non-sensory factors, the detailed definition of neurophysiological mechanisms of sensory conflict, remains an open and insufficiently researched topic [12].

The implementation of determining the position and orientation of the human body in space is based on a functionally organized structure called the spatial positioning system (SPS), which is based on the integration mechanisms of incoming sensory information [2]. The SPS provides orientation of the body in space both during movement and at a stationary position. The relatively stationary position of the human body is a convenient model for analyzing the peculiarities of SPS functioning. The vertical position of the body in space is inherently unstable, as the smallest deviation from the ideal vertical orientation occurs already due to gravitational forces, which accelerate the inclination of the body to the ground. Stability is achieved by creating appropriate compound torques those correct deviations from the desired orientation depending on signals from the sensory systems, primarily the proprioceptive, visual, and vestibular systems [13]. Functionally, the balance control can be viewed as a closed-loop feedback control system, with the integration of various sources of sensory information about orientation, being one component of the overall system [9]. Analyzing body sway caused by balance perturbations allows the measurement of “sensory weights”, which represent the relative contribution of the diverse sensory systems to an internal estimate of orientation, which in turn is used to generate corrective actions [22].

The most common measure for assessing and predicting the occurrence of deviations in the maintenance of postural stability is stabilometry, the main purpose of which is to assess the stability of a person in an upright position and to study the dynamics of their balance. In addition to assessing compensatory deviations of the human body, eye movement parameters can be recorded as they also contribute to postural stability [21]. Firstly, it is essential to consider the vestibulo-ocular reflex, which is a rotation of the eyeballs in the direction opposite to the head rotation due to the detection of angular acceleration by the semicircular channels of the vestibular apparatus. Secondly, optokinetic nystagmus, which is the two-phase eye movement that occurs when tracking a moving stimulus, can be considered as a reliable measure [8]. It consists of a phase of tracking the object and a return jump of the gaze to the initial fixation point. The parameters of vestibulo-ocular reflex integrity and optokinetic nystagmus are widely used in neurology as diagnostic indicators of correct functioning of the SPS.

Currently, virtual reality (VR) technologies are actively used for modeling optokinetic effects, by means of which the user's presence in an artificial three-dimensional environment is created [6]. The ability to create immersive visual and interactive virtual spaces expands the prospects of human perception and interaction with the surrounding virtual world. As a result, virtual reality technology finds wide application in various fields, including science, medicine, education, architecture, gaming industry and many others [20].

In the context of VR use, modeling optokinetic effects is crucial for creating a natural and realistic visual experience. When interacting with a virtual environment, the participant's gaze dynamics must adjust to changes in visual stimuli to ensure smooth and accurate tracking of moving objects, scenes, or points of interest, ultimately creating an immersive experience and deepening the user's immersion in the virtual environment [29]. Simulation of optokinetic stimulation in virtual reality can be created by using virtual optokinetic drums - usually these are virtual environments that represent a cylinder, the inner surface of which is colored in alternating black and white stripes. Such a cylinder can perform rotation around a vertical axis [14]. When an observer is placed in the center of such a virtual cylinder, compensatory body movements and eye movements of the optokinetic nystagmus type can be induced.

The rotation of the drum can also produce a motion sickness effect in the observer, the intensity of which will depend on the characteristics of the moving scene within such a drum, such as the speed of rotation (Mandour et al., 2021). A number of experiments have investigated the relationship between body sway and motion sickness intensity as a function of the width of the view field observed in a virtual reality environment when in helmet [28]. As a result, a reduced response of motion

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sickness and body sway formation was proved under conditions of gaze fixation on a stationary cross in front of moving strips of a rotating cylinder [26]. Thus, the relationship between the features of oculomotor behavior, the degree of sensory conflict severity, and postural stability was revealed [7].

It is important to note that the very appearance of discomfort sensations when observing a moving virtual scene represents a change in the functional state of the organism. In this respect, it can be considered as a model object for studying the dynamics of stress level changes, since the conditions of sensory conflict cause an adaptive response of the organism. Having in mind the control unit executed through eye movements, the process of sensory conflict formation when observing moving stimulation in virtual reality can be represented as a complex process of stress reaction development, which can be reflected in alterations of postural stability parameters.

AIMS AND HYPOTHESES

The aim of this study was to identify changes in brain activity and metrics of postural stability during induced stress exposure by disrupting the balance function in virtual reality.
The following hypotheses were advanced:

- Higher activity of the parietal regions of the brain will be observed with the increase of stimulation rotation speed in the virtual environment.
- The increased rotation speed of the stimulation in virtual reality will result in greater differences in stabilometric metrics.
- There is a relationship between changes in brain activity and stabilometric metrics when observing a moving virtual environment under different conditions of oculomotor activity implementation.

METHOD

STIMULATION

The virtual environment was a virtual optokinetic drum whose inner surface was colored with alternating black and white stripes 12 angular degrees wide each.

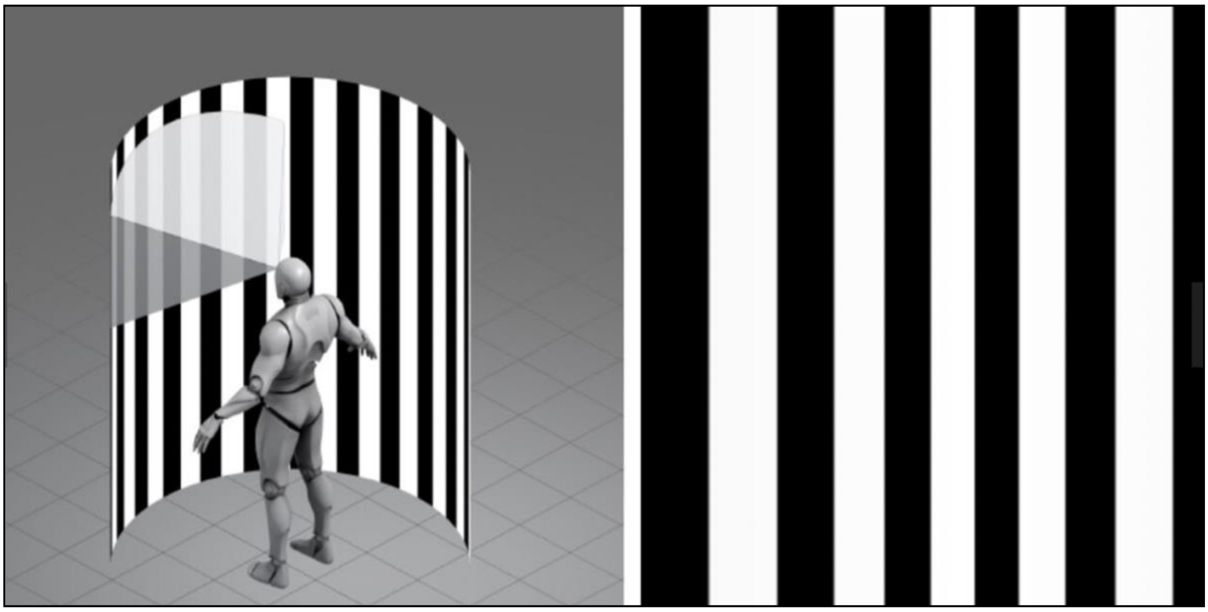

Figure 1. *Schematic illustration of the participant's position, visual field and optokinetic stimulus used in the experiment*

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The drum rotated horizontally around a vertical axis in two directions, clockwise and counterclockwise at two different angular velocities, 30 and 60 angular degrees per second. Each participant was given two instructions in two separate experimental conditions: first to fix their gaze in the center of the scene and second to track the movement of the drum stripes. Each rotation of the drum was performed for 1 minute at different speeds and directions of movement. A total of 8 rotations of the optokinetic drum were performed for each subject: 2 speeds, 2 directions, 2 conditions, and 2 repetitions. Additionally, the subjects were asked to press the controller button in order to indicate the moment when the illusion of body movement occurred and discomfort symptoms in the form of dizziness appeared. This type of stimulation was chosen due to a number of studies, the results of which showed that the perception of moving black and white stripes can provoke the occurrence of simulation disorder [15].

EQUIPMENT

Stimulation was presented in the VR system HTC Vive Pro Eye with the resolution of 2880 x 1600 (1440 x 1600 for each eye) and visual angle of 110°.

Figure 2. *HTC Vive Pro Eye VR helmet*

The ST-150 system was u ... state. Functional near-infrared 24-channel spectroscopy Brit ... hemodynamic response to circular impact executed by a virt ... ta acquisition and processing were performed in the Oxy Soft ... o the international 10-20% system, and measurements were t ...

The procedure included th ... e experiment. To pass the test, the participant stands on the ... ement - the inner line of the feet according to the markings ... pted coordinate system takes into account the position of ... g into account manually entered anthropometric paramete ... from the toe to the ankle joint in centimeters, body height.

Figure 3. *Hardware and software complex for stabilometry*

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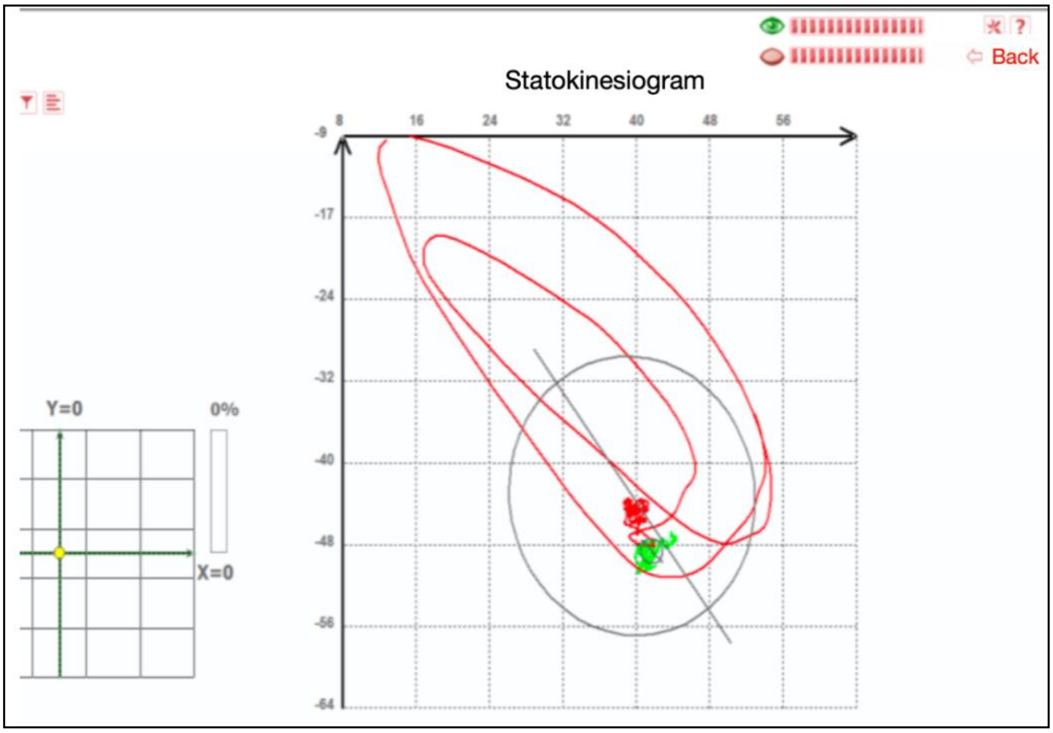

Figure 4. *Statokinesiogram display mode*

During the main stage of the experiment, the participants remained on the stabilometry platform while wearing a VR helmet with an optokinetic drum demonstration and fNIRS optodes placed on the head to record neural activity. The study was conducted using a two-series experimental design including a series with free oculomotor behavior and a series with arbitrary gaze fixation in the central region of the virtual environment. Optokinetic exposure was performed in two conditions of varying rotation speed (30 and 60 deg/s) and rotation direction (right and left). There were 4 cycles of each series repetition according to the following scheme:

1) Tracing eye movements following counterclockwise movement of the drum strips at a speed of 60 deg/s.
2) Tracing eye movements following clockwise movement of the drum stripes at a speed of 30 deg/s.
3) Tracing eye movements following clockwise movement of the drum stripes at a speed of 60 deg/s.
4) Tracing eye movements following counterclockwise movement of the drum stripes at a speed of 30 deg/s.
5) Fixation of the gaze in the center of the VR space while moving the drum strips counterclockwise at a speed of 60 deg/s.
6) Fixation of the gaze in the center of the VR space when moving the drum strips clockwise at a speed of 30 deg/sec.
7) Fixation of the gaze in the center of the VR space when moving the drum strips counterclockwise at a speed of 60 deg/sec.
8) Fixation of the gaze in the center of the VR space when moving the drum strips. clockwise at a speed of 30 deg/sec.

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The duration of cylinder rotation in each cycle was 1 minute. Each participant stood on the stabilometry platform in an upright and relaxed posture with arms along the body. During the main phase of the experiment a free statokinesiogram was recorded to measure postural control. The participants' task was to apply tracking eye-movement behavior and fixate their gaze in the central region of the virtual reality for each stimulus condition, and to provide a response by pressing a key on a computer keyboard when sensations of body position change in the virtual reality occurred. Between the series of conditions, the subjects rested for 3 minutes. After the main part of the experiment, Romberg foot placement test was carried out.

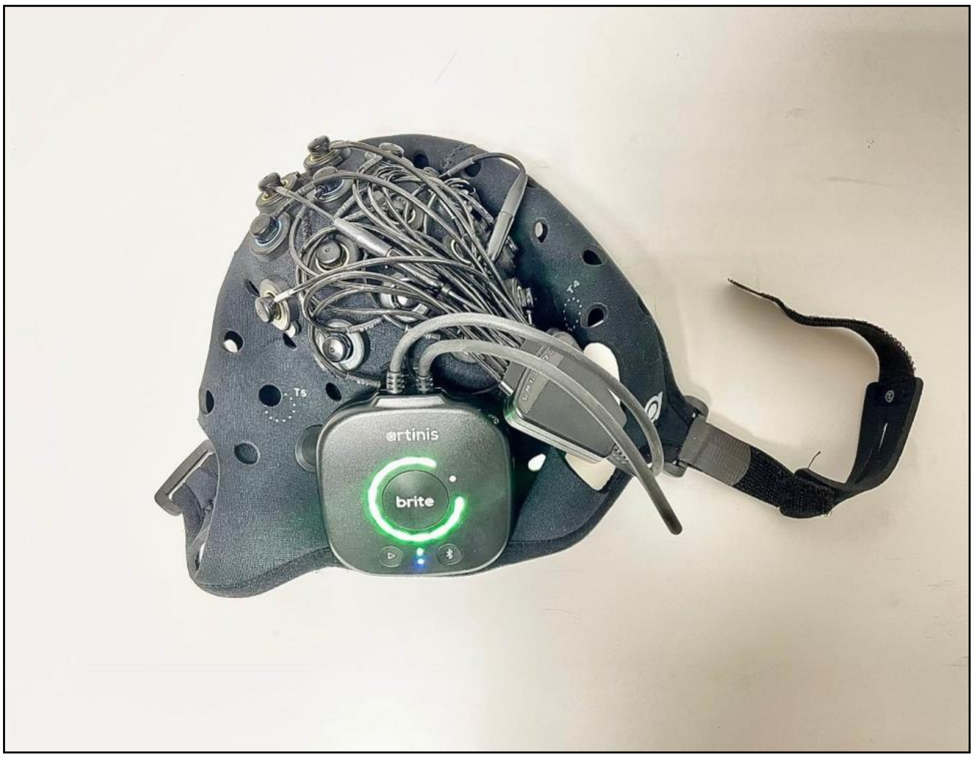

Figure 5. *27-ch fNIRS Artinis Brite wearable device*

RESPONDENTS

Twenty-six women (average age was 21 years) participated in the experiment. All subjects had normal or corrected to normal vision and no history of any neurological diseases.

RESULTS

The results were processed by means of two-factor analysis of variance with repeated measurements. The first factor was "Speed", which had two levels - 30 and 60 deg/s, respectively. The second factor was "Dynamics of gaze movement", 2 levels of which corresponded to the conditions of gaze fixation and tracing movements.

The following results were obtained on the basis of the conducted analysis:

Differences in the quality measures of the equilibrium function depending on the conditions of influence of the factor "Speed" were revealed (f=8.984b; df=1; p=<0.006). As a stabilometric indicator of the equilibrium function, center of pressure (COP) was applied. COP evaluates how minimal the velocity of the center of pressure on the support area is in order to maintain a stable upright vertical position. Maintaining the latter requires precise control of the neuromuscular system and maintaining a minimal fluctuation of the center of pressure on the footprint [23].

Fluctuations in the center of pressure are related to changes in the tonus of the muscles and limbs, as well as changes in the position of the gravity center. It is the COP index that is used as a more reliable indicator of the degree of statokinetic

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stability of a person's posture in comparison with generally accepted stabilographic indices. The COP value is in positive correlation with the quality of the balance function in the process of maintaining a person's upright posture. In this regard, the COP index allows to reveal the changes in balance under conditions of optokinetic influence of the VR environment.

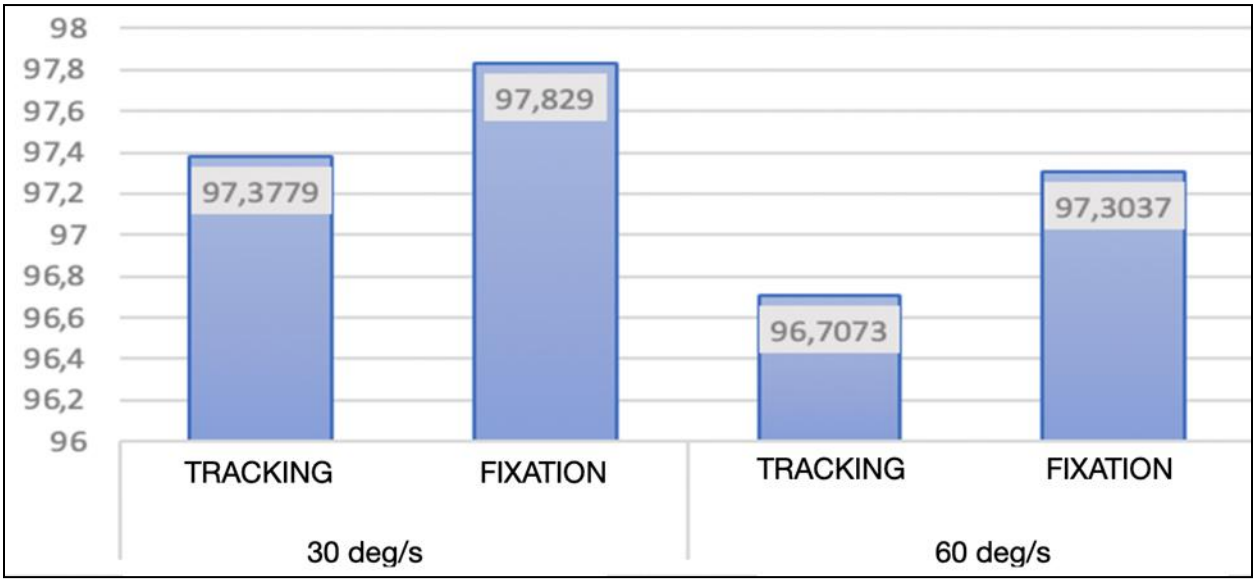

Figure 6. *Average value of center of pressure indices (%).*

Statistically significant differences of oxygenation level in the Rx8-Tx10 channel were obtained for the factors "Rotation Speed" (f=5.433b; df=1; p=<0.028), "Gaze Movement Dynamics" (f=5.433b; df=1; p=<0.025), "Rotation Speed + Gaze Movement Dynamics" (f=6.115b; df=1; p=<0.021).

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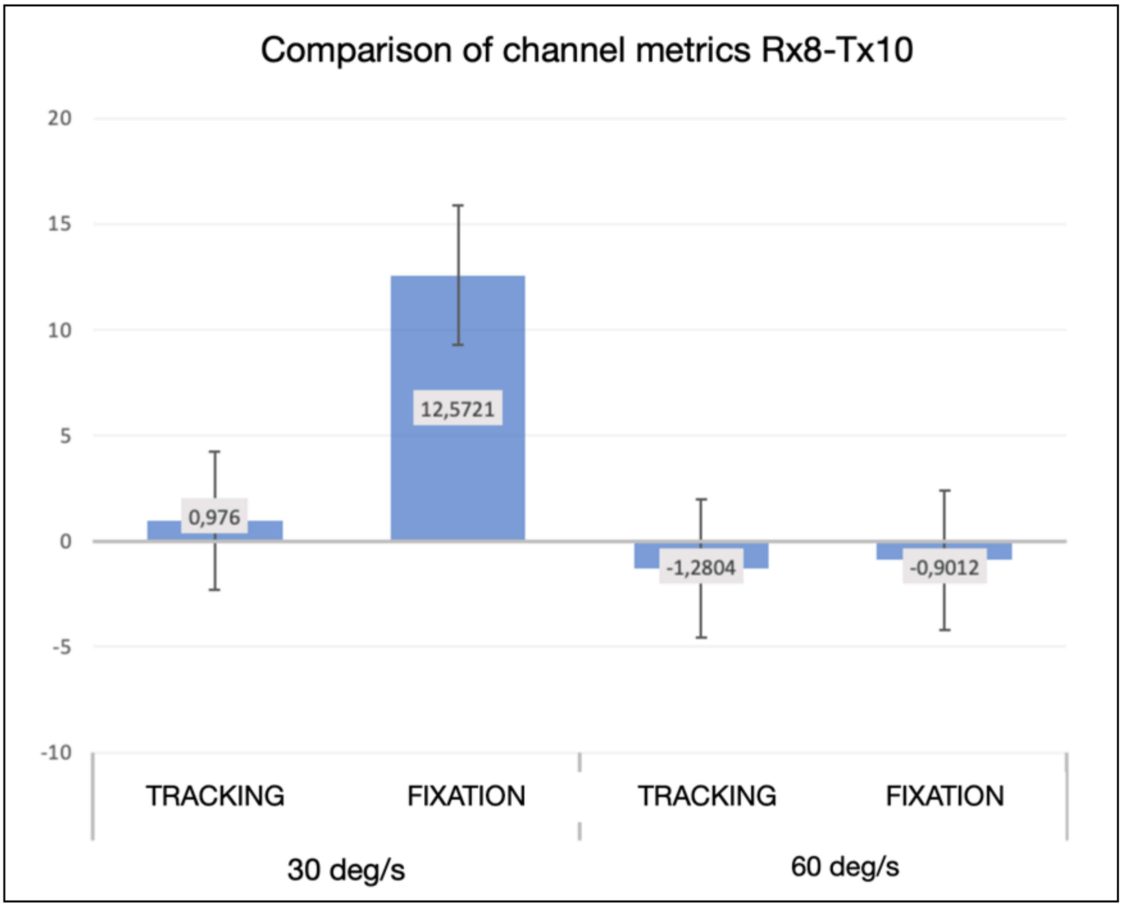

Figure 7. *Average values of oxygenation level for the factors "Rotation speed", "Gaze movement dynamics", "Rotation speed + Gaze movement dynamics"*

Statistically significant differences of oxygenation level in the Rx5-Tx7 channel were obtained for the factors "Gaze Movement Dynamics" (f=4.847b; df=1; p=<0.037), "Rotational Speed + Gaze Movement Dynamics" (f=5.327b; df=1; p=<0.030).

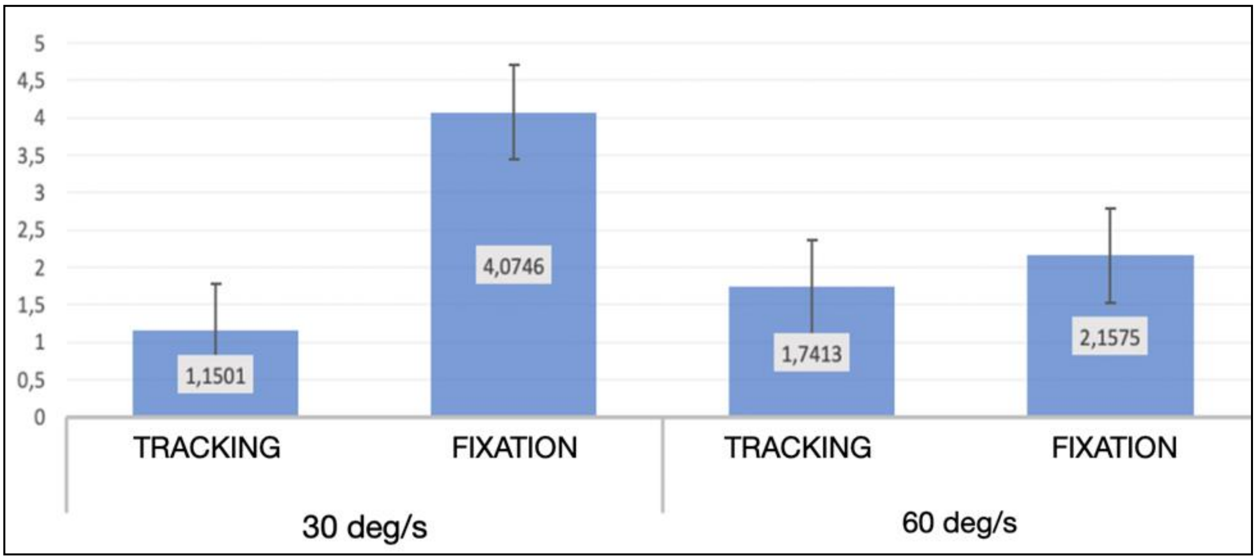

Figure 8. *Average values of oxygenation level for the factors "Dynamics of gaze movement", "Rotation speed + Dynamics of gaze movement", channel Rx5-Tx7.*

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Statistically significant differences of oxygenation level in the Rx3-Tx5 channel were obtained for the factors "Rotational speed + Gaze movement dynamics" (f=14.899b; df=1; p=<0.001).

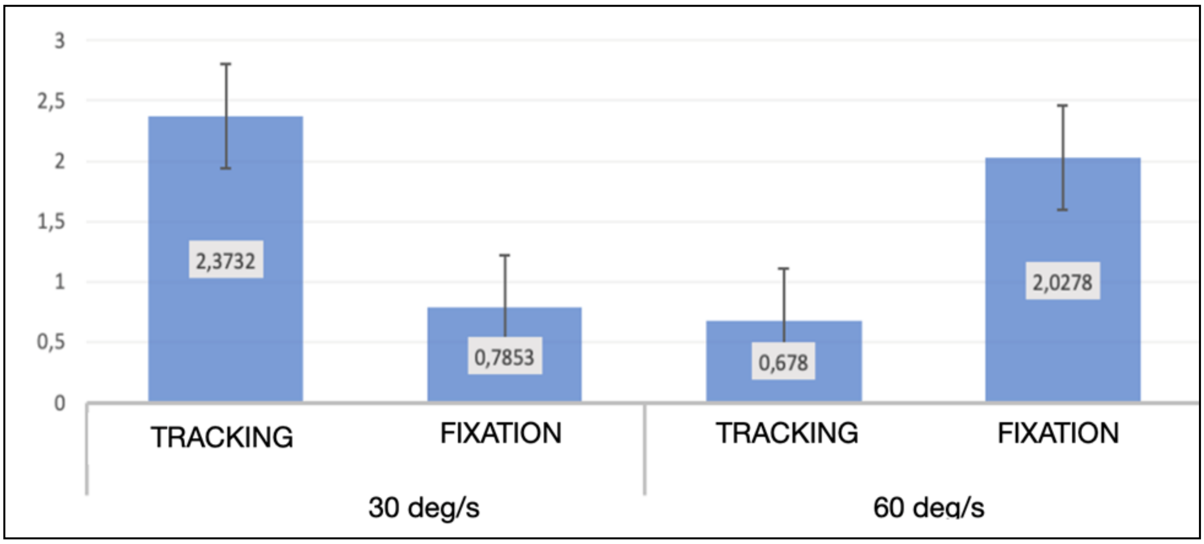

Figure 9. *Average values of oxygenation level for the factors "Rotation speed + Dynamics of gaze movement"*

DISCUSSION

The analysis of the quality of the balance function revealed statistically significant differences in the stabilometric indices when observing a moving virtual environment in different conditions of oculomotor activity realization, which confirms the proposed hypotheses.

Thus, in conditions of gaze fixation during optokinetic drum rotation at a speed of 30 deg/sec. an increased degree of stability of the human body position is observed. This speed is adaptive and comfortable for activation of reflex mechanisms responsible for maintaining balance and stability under conditions of changing vestibular input. Visual control with a fixed gaze at the point of the rotating object, namely drum, allows the balance system to provide more accurate information about the movement and position of the human body in space [19]. When an external object rotates, the vestibular system and visual receptors transmit multidirectional signals to the brain, which activates reflex mechanisms to correct body position [31]. The system of vestibular correction in combination with visual control allows to effectively compensate for changes in the position of the head and body of the person in space during the rotation of the drum. This leads to improved stability and accuracy of movements, preventing loss of balance and enhancing the quality of balance function under conditions of alternating exposure to external stimuli, the obtained results are in line with previously conducted experiment [30].

The lowest COP was obtained under conditions of tracing gaze movement when the optokinetic drum was rotated at a speed of 60 deg/sec. This is due to the fact that the speed of the object rotation is much higher than the adaptation capacity of the vestibular and visual systems. Therefore, there is a disintegration between the perception of body motion in space, which leads to dissonance of signals arriving in the central nervous system and hinders the correct assessment of the position of the body relative to the surrounding space, thereby manifesting in the deterioration of the balance function quality [3]. In such conditions, the human body has difficulty in maintaining a stable position and balance due to impairments in the processing of position and motion information in space.

The findings show that the parietal region in the right hemisphere and the occipital region of the brain were highly oxygenated during circular vectoring, this is partially consistent with the theory of reciprocal inhibition between visual and vestibular cortex [17]. The obtained results of brain activity measurements in a combination of different factor conditions demonstrated increased oxygenation in the following channels:

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Channels Rx8-Tx10 and Rx5-Tx7 showed increased oxygen saturation at lower speeds under conditions of gaze fixation instruction, these channels were located in the right parietal area of the brain. This result also finds support in other studies in which neuroimaging technologies were used. In 2011. A. Kleinschmidt and colleagues [16] used fMRI to show activation of the parietal area in the event of a sensory conflict. This was the reason to consider the parietal cortex, and in particular the ventral intraparietal zone, as the area of "switching" the stable perception of the position of one's body in space to an unstable one during a sensory conflict. Thus, hypothesis №2 was confirmed.

Channel Rx3-Tx5 revealed increased oxygenation under tracking conditions when the optokinetic drum is rotated at a speed of 30 deg/sec and under fixation conditions when the optokinetic drum is rotated at a speed of 60 deg/sec. The localization of this channel is placed in the left parietal region and illustrates the result of adaptation of the visual system. Since the interaction between the visual and vestibular system is reflected in the operation of the vestibulo-ocular reflex (VOR) [18]. Eye movement can only be induced by stimulation of the vestibular system, and the VOR stabilizes the image in the visual field. The VOR is a precise and rapid process that is crucial for maintaining gaze stability during movement and is independent of the visual signal [27]. The findings are comparable to previous studies that demonstrated the existence of reciprocal inhibition between the visual and vestibular systems at target areas of the right hemisphere brain to measure a signal responsive to physical movement [11]. Compared to the overall increase in HbO concentration, the Rx3-Tx5 channel showed a decrease in HbO levels in the gaze fixation condition. The synchronized phenomenon may be related to the functional inhibitory mechanism of the brain. The Rx8-Tx10 and Rx5-Tx7 channels may be the most representative of the intratemporal region. Considering the inference from the 10-20 system, the brain activation region found in our study is in high agreement with previous vestibular brain mapping studies [5] on how cortical areas are activated under different movement conditions. In this way, hypotheses №2 and №3 were confirmed.

CONCLUSIONS

The experiment revealed the dependence of hemodynamic response on the nature of oculomotor activity under optokinetic influence. Differences in the brain activity changes, when observing a moving virtual environment depend on different conditions of oculomotor activity realization, may be due to the activation variability of different sensory systems, reflex mechanisms and neural pathways responsible for processing visual information and maintaining balance in different conditions of virtual perception. The fact that activation differences in the parietal region were found depending on the conditions of eye movements suggests more complex mechanisms of "switching" operation, including the control system of oculomotor activity. Thereby, the specificity of neurophysiological mechanisms underlying sensory conflict as one of the illustrative ways of changing the functional state of a person under virtual reality conditions was shown. Thus, this study with the use of fNIRS demonstrated the presence of a pronounced reaction of increasing blood oxygen saturation in parietal cortical areas at different patterns of eye movements under virtual reality conditions.

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